ACTA UNIVERSITATIS SZEGEDIENSIS

ACTA MINERALOGICA-PETROGRAPHICA

FIELD GUIDE SERIES

Volume 29 Szeged, 2010

XC 63012

PETER KODĚRA & JAROSLAV LEXA

Classic localities in Central Slovakia Volcanic Field: Gold, silver and base metal mineralizations and mining history at Banská Štiavnica and Kremnica

IMA2010 FIELD TRIP GUIDE SK3

20th General Meeting of IMA · Budapest, 21–27 August, 2010

Published by the Department of Mineralogy, Geochemistry and Petrology, University of Szeged

ACTA MINERALOGICA-PETROGRAPHICA
estabilished in 1923

FIELD GUIDE SERIES

HU ISSN 0324-6523
HU ISSN 2061-9766

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This volume was published for the 375th anniversary of the Eötvös Loránd University, Budapest.

EÖTVÖS UNIVERSITY PRESS

The publication was co-sponsored by the Eötvös University Press Ltd., Budapest.

IMA2010 (www.ima2010.hu) is organised in the frame of the ELTE375 scientific celebration activities.

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The Acta Mineralogica-Petrographica is published by the Department of Mineralogy, Geochemistry and Petrology, University of Szeged, Szeged, Hungary

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ISBN 978-963-306-061-2

On the cover: Sv. Trojica (Trinity) Square, Banská Štiavnica, Slovakia. On the right: Berggericht from the 16th century, former seat of the Mining Court, later used by the Mining Academy, now home of the mineralogical exhibition of the Slovak Mining Museum. Photo: Peter Koděra.

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Acta Mineralogica-Petrographica, Field Guide Series, Vol. 29, pp. 1–19.

ACTA Mineralogica Petrographica

Classic localities in Central Slovakia Volcanic Field: Gold, silver and base metal mineralizations and mining history at Banská Štiavnica and Kremnica

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1. Central Slovakia Volcanic Field

The famous classical mining regions of Banská Štiavnica and Kremnica are hosted by the Central Slovakia Volcanic Field, which is situated on the inner side of the Carpathian arc and covers over 5000 km^2 in area (Fig 1; Konečný *et al.*, 1995). During the Neogene, the Carpathians represented an advancing continental margin to an island arc that migrated north-eastward at the expense of a subducting oceanic crust of flysch basins, until it collided gradually with the passive margin of the European platform (Royden *et al.*, 1982). Advance of the arc caused by subduction roll-back was compensated by back-arc extension involving the upwelling of the asthenospere. Volcanic rocks of the Badenian to Pannonian age (16.5–8.5 Ma) are closely associated with basin and range extension tectonics (Lexa & Konečný, 1998; Konečný *et al.*, 2002). Calc-alkaline rocks show a medium- to high-K trend similar to andesites of continental margins or evolved island arcs involving older continental crust (Lexa *et al.*, 1998a). Isotopic data point to mantle source magmas with a considerable crustal contamination (Salters *et al.*, 1988). Harangi & Lenkey (2007) concluded that the primary magmas were formed during the peak phase of the

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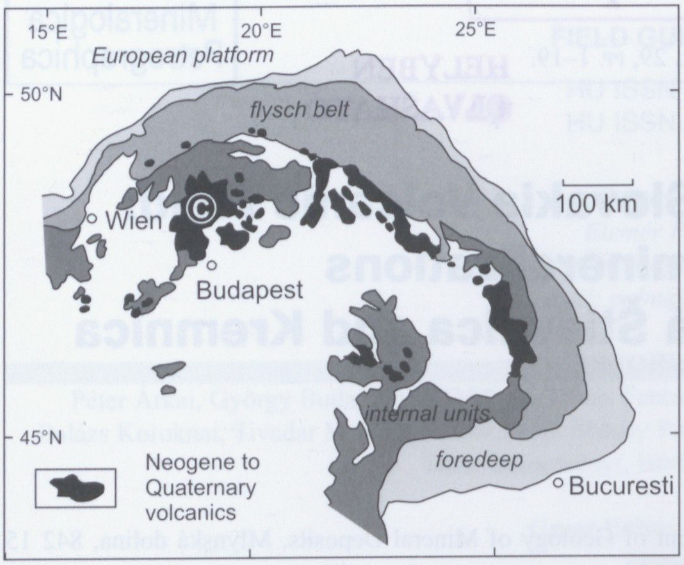

Fig. 1. Position of the Central Slovakia Volcanic Field (C) among the Neogene to Quaternary volcanic rocks in the area of the Carpathian arc and Pannonian basin (after Lexa *et al.*, 1999a).

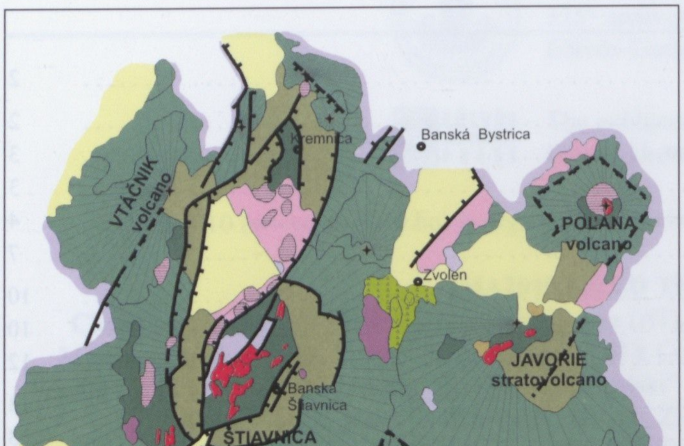

Fig. 2. Structure of the Central Slovakia Neogene Volcanic Field including Banská Štiavnica stratovolcano and Kremnické Vrchy Mts. (Lexa *et al.*, 1999a).

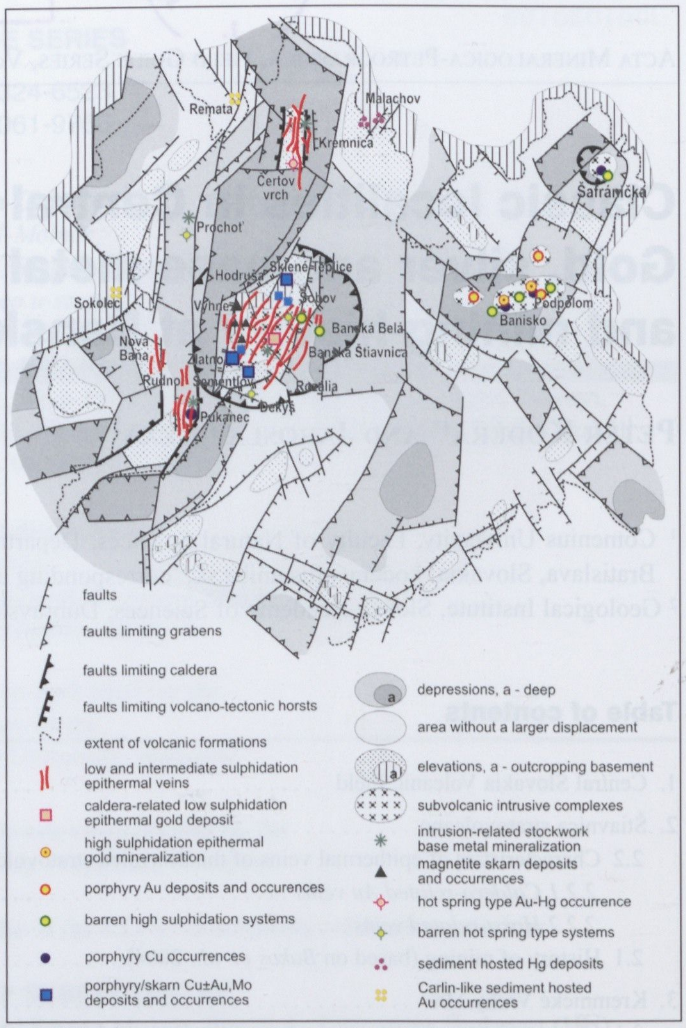

Fig. 3. Basement structure and metallogenetic scheme of the Central Slovakia Volcanic Field (Lexa, 2005).

extension by melting of metasomatized, enriched lithospheric mantle. Further evolution of magmas towards andesitic composition took place by high-pressure fractionation at the base of the crust and by low-pressure fractionation, assimilation and mixing in shallow magma chambers towards dacitic composition. Associated crustal anatexis led to the evolution of anatectic rhyolitic magmas (Lexa *et al.*, 1998a).

The tectono-thermal activization of the back-arc basins related to the thinning of the crust and lithosphere and updoming of the asthenosphere played an important role in magma generation as well as in metallogenetic processes. Coincidence of increased heat flow, magmatic activity and back-arc extension creating pathways for hydrothermal fluids were crucial factors. Mineral deposits in the Central Slovakia Neogene Volcanic Field are hosted by central zones of large andesite stratovolcanoes involving volcanotectonic depressions, resurgent horsts, extensive subvolcanic intrusive complexes and complexes of differentiated rocks (Figs. 2, 3).

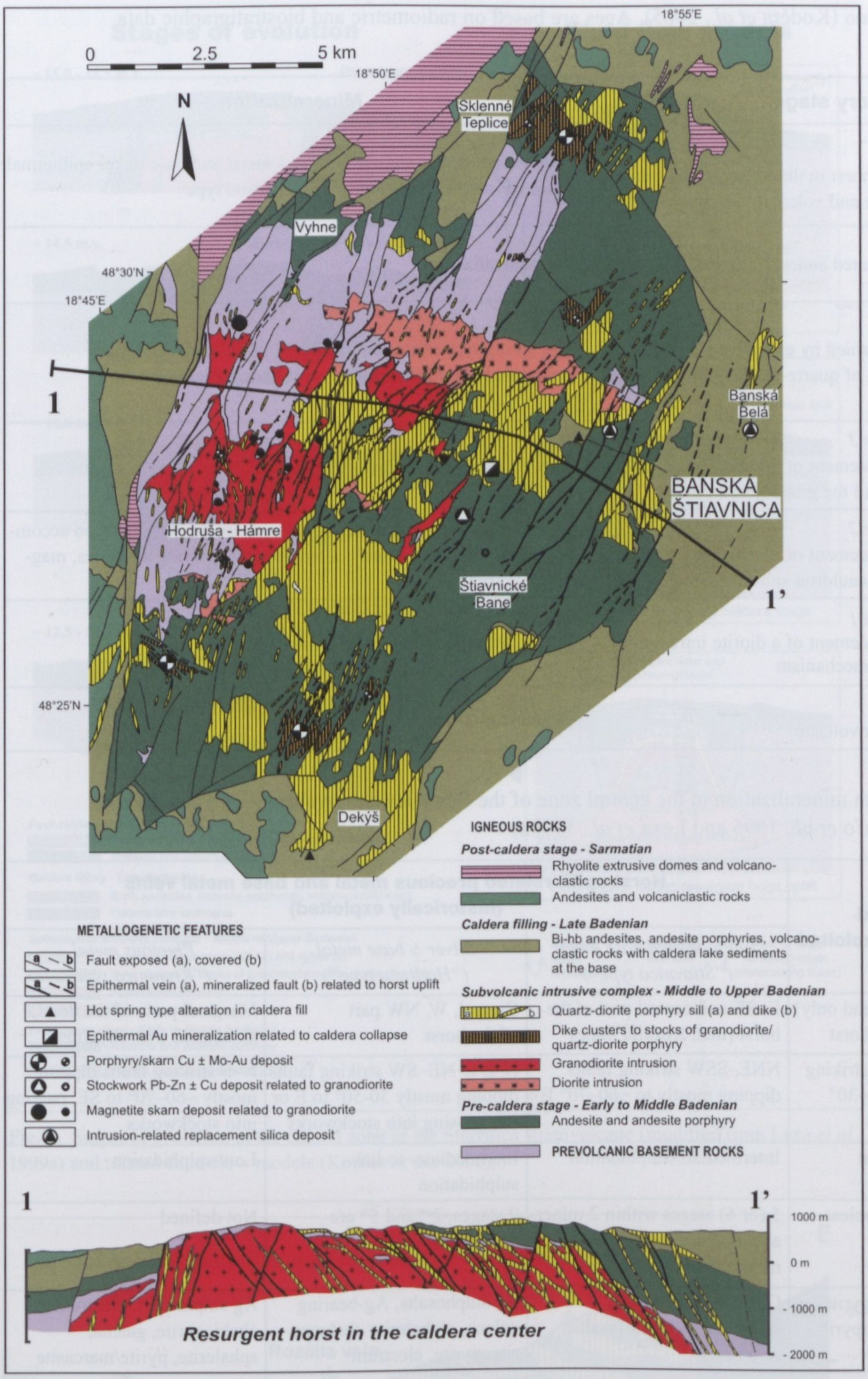

Fig. 4. Structural scheme and schematic E-W cross section of the central zone of the Štiavnica stratovolcano, represented by a resurgent horst in the centre of the caldera (after Lexa *et al.*, 1999a).

2. Štiavnica stratovolcano

The Štiavnica stratovolcano is situated in the southern part of the Central Slovakia Volcanic Field. This stratovolcano with a diameter of almost 50 km covers some 2000 km^2 and is the largest volcano in the whole Carpatho-Pannonian area. An extensive caldera 20 km in diameter, a voluminous subvolcanic intrusive complex and a late-stage resurgent horst in the caldera centre accompanied by rhyolite volcanites are the most characteristic features (Fig 2; Konečný *et al.*, 1995). As the resurgent horst uplift was asymmetric, erosion in its NW part has reached basement rocks and subvolcanic intrusions of diorite, granodiorite and granodiorite to quartz-diorite porphyry (Fig. 4).

According to Konečný *et al.* (1998), evolution of the Štiavnica stratovolcano took place in five stages (16.5–10.5 Ma; Table 1, Fig. 5). Its evolution started with the formation of a large andesite stratovolcano, followed by denudation and emplacement of several subvolcanic intrusions, dominated by a granodiorite pluton. Later, caldera subsidence and emplacement of quartz-diorite porphyry sills and dykes took place. A renewed post-caldera andesitic volcanism followed. Finally a long-lasting resurgent horst uplift in the centre of the caldera was associated with rhyolitic volcanic activity. Evolution of the volcano was accompanied by various types of hydrothermal alteration and mineralization, ranging from early intrusion-related, subvolcanic skarns and porphyry copper systems to late, high-level, base- and precious-metal epithermal veins (see summary in Table 1).

Epithermal veins were formed during two major evolutionary stages. The recently discovered early Au-Ag veins of the intermediate sulphidation type were related to hydrothermal activity during the early stage of the caldera collapse (Koděra *et al.*, 2005). Later post-caldera Ag-Au-Pb-Zn-Cu veins of intermediate to low sulphidation type were associated with hydrothermal activity during long-lasting uplift of the resurgent horst in the centre of the caldera (Table 2).

2.1 Characteristics of epithermal veins of the Štiavnica stratovolcano

2.1.1 Caldera-related Au veins

The relatively oldest epithermal vein system in the centre of this district occurs within subhorizontal structures that formed as the result of a collapse-related stress field (Koděra *et al.*, 2005). Till now, these veins are known to occur only at deep levels of the historic Rozália base metal mine in Banská Hodruša (400–650 m below surface). The Au mineralization

Table 1. Evolution of the Štiavnica stratovolcano (Koděra *et al.,* 2005). Ages are based on radiometric and biostratigraphic data (Konečný *et al.,* 1983, 1998)

Age (Ma)	Evolutionary stage	Mineralization
10.5 to 12.5	*Resurgent horst / rhyolite stage* Long-lasting uplift of a resurgent horst in the centre of the caldera, accompanied by rhyolitic intrusive and volcanic activity	Extensive zoned system of precious metal and base metal epithermal veins of intermediate- to low-sulphidation type
12.5 to 14.0	*Post-caldera andesite stage* Renewed activity of less differentiated andesites in and around the caldera	No mineralization
14.0 to 14.5	*Caldera stage* Subsidence of the caldera accompanied by extrusive activity of differentiated andesite. Emplacement of quartz-diorite sills and dykes by ring-dyke mechanism	Hot spring type alteration in caldera infill; low-sulfidation epithermal Au mineralization on subhorizontal veins
14.5 to 15.5	*Subvolcanic intrusion stage, phase 3* Denudation of the volcano. Emplacement of granodiorite to quartz-diorite dyke clusters / stocks around the granodiorite pluton	Cu± Au, Mo skarn-porphyry mineralization
	Subvolcanic intrusion stage, phase 2 Denudation of the volcano. Emplacement of an extensive granodiorite bell-jar pluton by underground cauldron subsidence mechanism	Stockwork base metal mineralization in apical part of pluton accompanied by advanced-argillic alteration in overlying andesites, magnetite skarns
	Subvolcanic intrusion stage, phase 1 Denudation of the volcano. Emplacement of a diorite intrusion by underground cauldron subsidence mechanism	Barren lithocap of advanced argillic alteration
15.8 to 16.2	*Pre-caldera andesite stage* Formation of a large andesite stratovolcano	No mineralization

Table 2. Basic characteristics of epithermal vein mineralization in the central zone of the Štiavnica stratovolcano (summarized from Kovalenker *et al.,* 1991, Maťo *et al.,* 1996 and Lexa *et al.,* 1999a)

	Caldera–related Au veins currently exploited	Horst uplift-related precious metal and base metal veins (historically exploited)		
		Sulphide-rich base metal ("Štiavnica type")	*Silver ± base metal ("Hodruša type")*	*Precious metal ("Kremnica type")*
Location	Rozália mine (underground only) in W central part of the horst	E, SE and central part of the horst (incl. Rozália mine)	Central, W, NW part of the horst	Marginal parts of the horst, associated with rhyolites
Structures	ENE–WSW to NE–SW striking faults dipping mostly 20–30° rarely up to 70° to SW	NNE–SSW striking faults dipping mostly to ~60–70° E	N–S to NE–SW striking faults dipping mostly 30-50° to E or SE, passing into stockworks	N–S striking faults dipping mostly ~60–70° to SE, passing into stockworks
Mineralization type	Intermediate-sulphidation	Intermediate-sulphidation	Intermediate- to low-sulphidation	Low-sulphidation
Mineralization stages	2 stages + 3rd stage of unclear position	5 (or 6) stages within 2 mineralization cycles and distinct metal vertical zoning	9 stages, 2nd and 5th are ore-bearing	Not defined
Major ore minerals	Native gold, electrum?, pyrite, sphalerite, galena, chalcopyrite	Chalcopyrite, galena, sphalerite ± Ag sulfosalts, electrum	Ag sulphosalts, Ag-bearing galena, s(phalerite chalcopyrite, pyrite, electrum	Ag sulphosalts, electrum ± chalcopyrite, galena, sphalerite, pyrite/marcasite
Major gangue minerals	Quartz, carbonate	Quartz, carbonate	Quartz, carbonate	Quartz, carbonate
Ag-Au ratio of ores	1:2 to 10:1	10:1 to 20:1	100:1	1:1 to 10:1
Alteration	Illite, minor adularia, quartz, calcite	Illite, quartz, minor adularia,	Illite, adularia, quartz; outward zone of mixed-layer I/S and Ch/S clay minerals	Quartz, adularia, sericite; outward zone of mixed-layer I/S and Ch/S clay minerals

typically occurs in banded veins and veinlets and in silicified hydrothermal breccias at the base of pre-caldera andesites, close to the roof of a subvolcanic granodiorite intrusion (Fig. 6). The veins are dismembered by a set of quartz-diorite porphyry sills and displaced by the younger, steeply-dipping, Rozália base-metal vein, and parallel structures related to resurgent horst uplift in the caldera centre. The thickness of individual veins is between 0.1–2 m with gold contents varying from 5 to 600 g/t, and averaging 20 to 50 g/t, with Ag/Au ratio varying from 1:2 to 10:1, depending on the mineralization stage. Native gold of microscopic size is the dominant form of gold (Maťo *et al.,* 1996). The accompanying alteration consists of

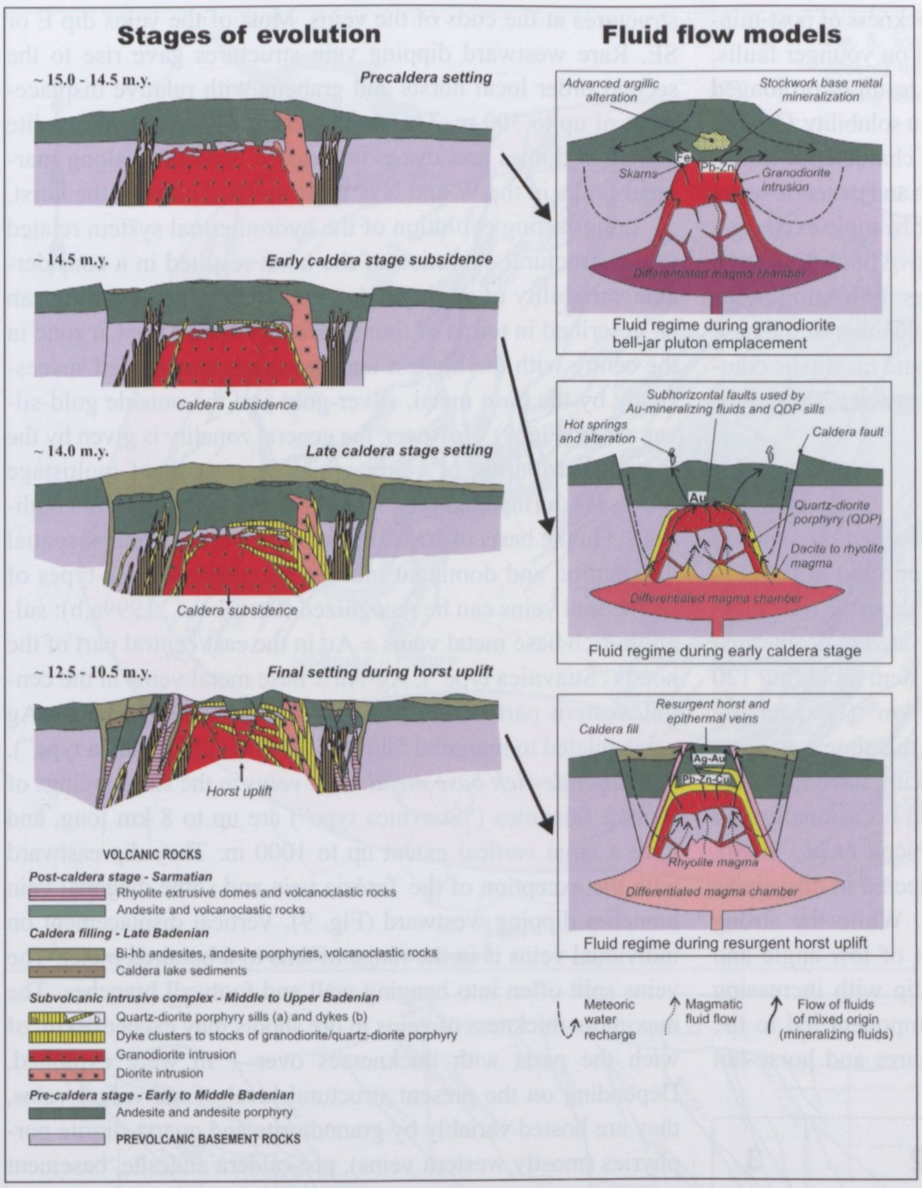

Fig. 5. Stages of evolution in the central zone of the Štiavnica stratovolcano (modified from Lexa *et al.*, 1999a) and related fluid-flow models (Koděra *et al.*, 2005).

illite, minor adularia and disseminated quartz and carbonates.

Maťo *et al.* (1996) distinguished three stages of mineralization (Fig. 7). Stage 1 corresponds to pervasive silicification and pyritization, and involves the formation of early subhorizontal veins with milky quartz and silicified breccias. Quartz is accompanied by carbonates (Mn-rich calcite, Fe-rich dolomite, siderite), minor sphalerite (8.2–11.2 mol% FeS) and rare gold of high purity (90.5–95.8% Au). Stage 2 is represented by quartz, rhodonite, carbonates (rhodochrosite/Mn-rich calcite, Fe-rich dolomite, siderite), pyrite, gold of lower purity (80.6-87.8% Au), lower FeS sphalerite (1.7–4.3 mol% FeS), galena and chalcopyrite. Stage 3 results from the second stage of deformation (horst uplift) and includes quartz, Fe/Ca carbonate, pyrite, sphalerite (0.4–1.9 mol% FeS), galena, chalcopyrite, tetrahedrite, polybasite, hessite, and gold of low fineness (73.9–78.8 % Au electrum).

Au mineralization took place from fluids of low salinity (0–3 wt% NaCl eq.) that underwent extensive boiling at moderate temperatures (280–330 °C). Variable pressure conditions (39–95 bars) indicate a continual opening of the system and a transition from suprahydrostatic towards hydrodynamic conditions at shallow depths (~550 m). The estimated paleodepth coincides with the present vertical distance between the Au mineralization and the base of the caldera filling, which

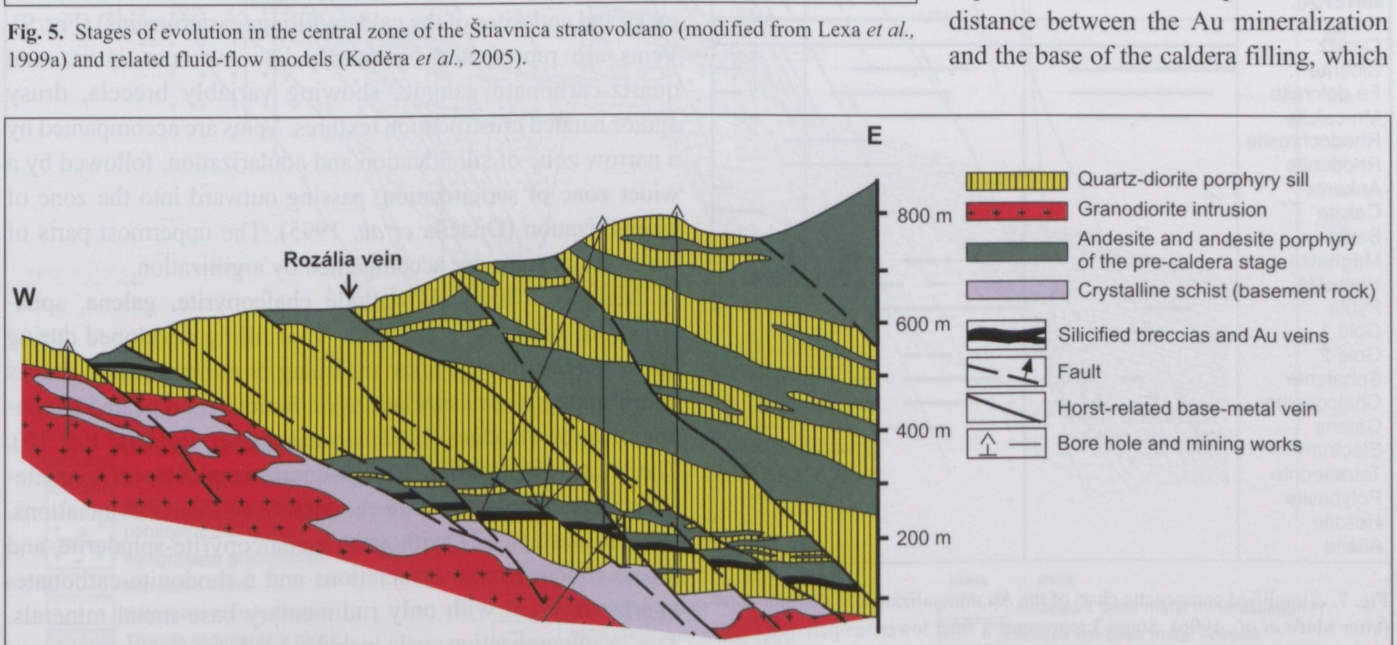

Fig. 6. Schematic cross section of the caldera-collapse related Au epithermal deposit at the 14th level of the Rozália mine (after Šály & Prcúch, 1999).

is roughly 500-600 m, if corrected for the thickness of post-mineralization porphyry sills and displacement on younger faults. Precipitation of Au is considered to be the result of prolonged boiling of fluids and associated decrease in Au solubility. Oxygen and hydrogen isotope data suggest a mixed character of fluids, falling between the fields of typical magmatic and meteoric water influenced by $\delta^{18}O_{fluid}$ shift due to fluid-rock isotopic exchange. Caldera subsidence established new, convective fluid-flow paths along marginal caldera faults which acted as infiltration zones (Fig. 5). A shallow, differentiated magma chamber at the base of the volcano was the likely source of heat and magmatic components for the mineralizing fluids (Koděra *et al.,* 2005).

2.1.2 Horst-related veins

The younger system of epithermal veins evolved on and was controlled by faults of the resurgent horst uplifted in the central part of the caldera. The uplift lasted almost 2 mil. years (~12.5–10.7 Ma, Lexa *et al.,* 1999a). Associated hydrothermal activity formed an extensive epithermal system including 120 veins and veinlets, covering almost 100 km^2 (Lexa *et al.,* 1999a; Fig. 8). Regional stress field during this time was dominated by a strong NW–SE extension, with the maximum stress axis mostly in subvertical position, but occasionally also in subhorizontal NE–SW orientation (Nemčok *et al.,* 2000). This configuration of the stress field is reflected in dip-slip as well as oblique movements of the veins. While the strong extension lead eventually to the evolution of low-angle and lystric vein structures with a decreasing dip with increasing depth, the dextral lateral displacement component led to the evolution of ore shoots, en-echelon structures and horse-tail structures at the ends of the veins. Most of the veins dip E or SE. Rare westward dipping vein structures gave rise to the second order local horsts and grabens with relative displacement of up to 300 m. The emplacement of associated rhyolite extrusive domes and dykes took place especially along marginal faults in the W and NW most uplifted parts of the horst.

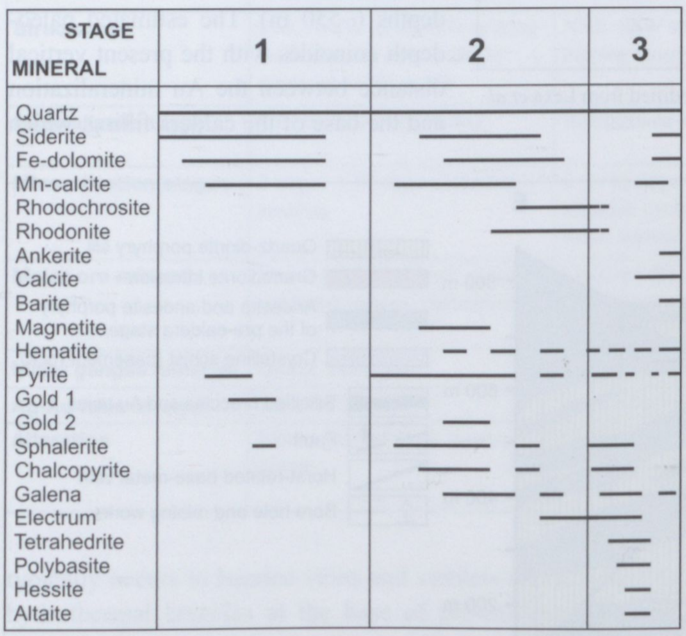

Fig. 7. Simplified paragenetic chart of the Au mineralization at Rozália mine (after Maťo *et al.,* 1996). Stage 3 represents a final lower temperature overprint and cannot be readily distinguished from the mineralization of the Rozália vein and parallel veinlets.

Long-lasting evolution of the hydrothermal system related to the structural evolution of the horst resulted in a considerable variability of epithermal veins. Their general zoning can be described in terms of four concentric zones: the Cu zone in the centre with the highest temperature is surrounded successively by the base metal, silver-gold and the outside gold-silver zones (Fig. 8). However, the general zonality is given by the spatial distribution of veins, which is a result of multistage processes during changing structural and hydrothermal conditions. On the basis of structural aspects, vertical extent, spatial distribution and dominant mineral paragenesis three types of epithermal veins can be recognized (Lexa *et al.,* 1999a,b): sulphide-rich base metal veins ± Au in the east/central part of the horst ("Štiavnica type"), Ag-Au ± base metal veins in the central/western part of the horst ("Hodruša type"), and Au-Ag veins related to marginal faults of the horst ("Kremnica type").

Sulphide-rich base metal ± Au veins in the surroundings of Banská Štiavnica ("Štiavnica type") are up to 8 km long, and have a large vertical extent up to 1000 m. They dip eastward with the exception of the Terézia vein and some diagonal vein branches dipping westward (Fig. 9). Vertical displacement on individual veins is in the range of tens to a hundred meter. The veins split often into hanging wall and footwall branches. The maximum thickness of veins in ore shoots may exceed 10 m, of wich the parts with thicknesses over 1 m were exploited. Depending on the present structural level of individual veins, they are hosted variably by granodiorite and quartz-diorite porphyries (mostly western veins), pre-caldera andesite, basement rocks and andesites of the caldera filling (eastern veins) (Fig. 9). Veins are represented by mostly by cavernous quartz and quartz-carbonate gangue, showing variably breccia, drusy and/or banded crustification textures. Veins are accompanied by a narrow zone of silicification and adularization, followed by a wider zone of sericitization, passing outward into the zone of propylitization (Onačila *et al.,* 1995). The uppermost parts of the external veins are accompanied by argillization.

Major ore minerals include chalcopyrite, galena, sphalerite, Ag sulphosalts and gold. Vein filling developed during two mineralization cycles including 5 mineralization stages and 11 paragenetic associations on faults with repeated tectonic activation (Koděra, 1963; Kovalenker *et al.,*1991; Fig. 10). The 1st cycle includes a hematite-quartz stage (1) with hematite-quartz and minor rhodonite-rhodochrosite-quartz associations, sphalerite stage (2) with galena-chalcopyrite-sphalerite and quartz-rhodochrosite associations and a rhodonite-carbonate-quartz stage (3) with only rudimentary base metal minerals. The 2nd mineralization cycle includes a galena-chalcopyrite stage (4) with rare Au-Ag-Cu-Pb-Bi minerals and native gold, volu-

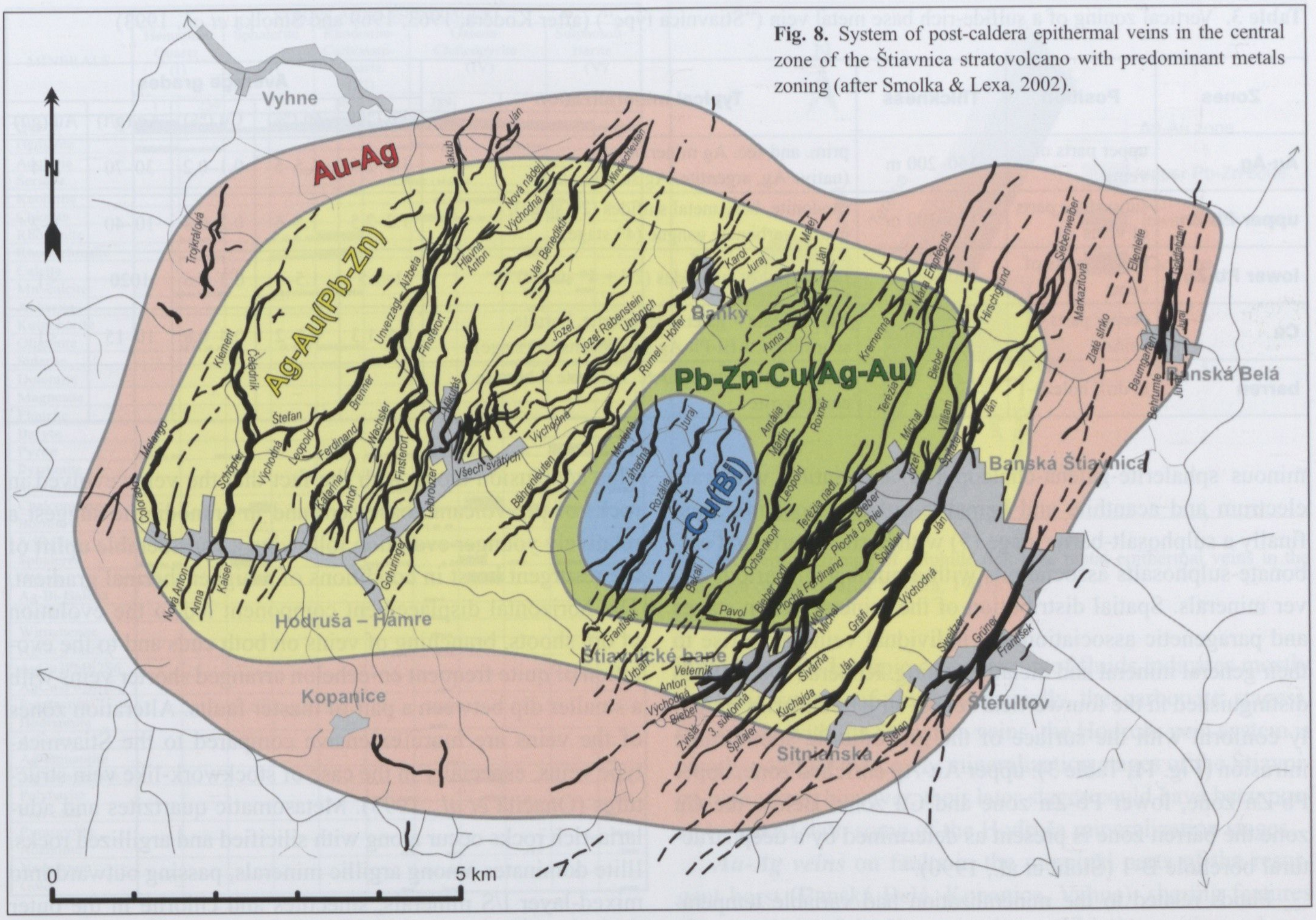

Fig. 8. System of post-caldera epithermal veins in the central zone of the Štiavnica stratovolcano with predominant metals zoning (after Smolka & Lexa, 2002).

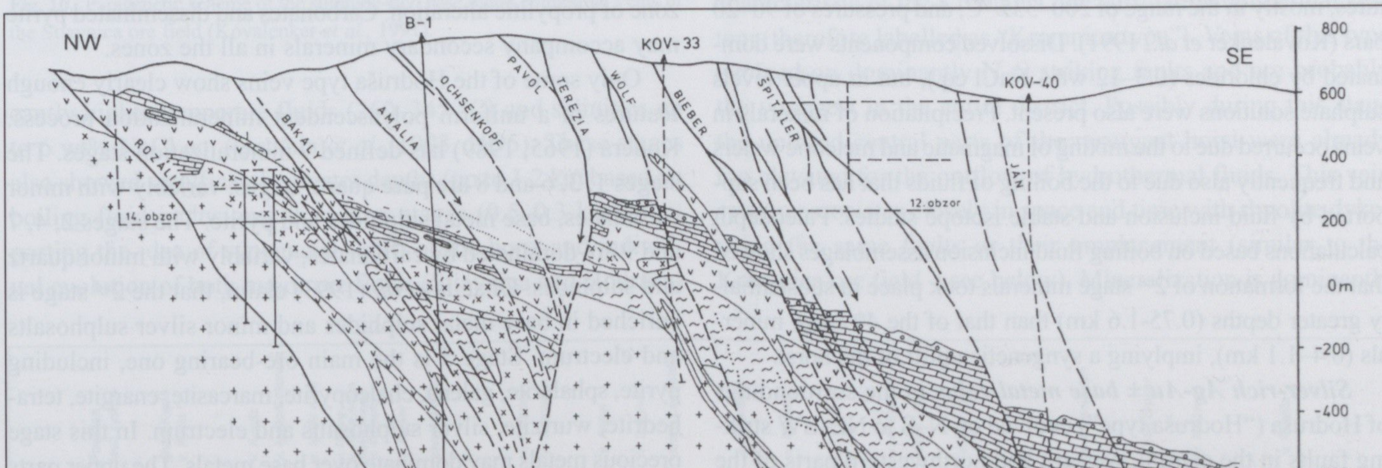

Fig. 9. Transverse sections of the system of sulphide-rich base metal epithermal veins in the Štiavnica ore field SW of Banská Štiavnica (Štohl *et al.*, 1990).

Table 3. Vertical zoning of a sulfide-rich base metal vein ("Štiavnica type") (after Koděra, 1963, 1969 and Smolka *et al.*, 1993)

Zones	Position	Thickness	Typical mineralization	Average grades				
				Pb (%)	Zn (%)	Cu (%)	Ag (g/t)	Au (g/t)
Au-Ag	upper parts of veins	150–200 m	prim. and sec. Ag minerals (native Ag, argentite, Ag sulphosalts)	1.5–2.5	1.5–5	0.1–0.2	30–70	2–4
upper Pb-Zn	subsurface parts of veins	150–300 m	rhodonite, base metal sulfides (2nd stage), quartz-carbonate gangue (4th stage)	1.2–2.5	1.5–5	0.2–0.4	10–40	1–2
lower Pb-Zn	middle parts of veins	300–400 m	base metal of sulphides (2nd + 4th stages)	1–1.5	1.5–3	0.3–0.6	1020	<1
Cu	deeper parts of veins	up to 500 m	chalcopyrite > galena, sphalerite, bornite, scheelite, Cu-Bi-Pb-Ag sulphosalts (4th stage)	0.5–1.3	0.5–2	0.4–0.8	10–15	<1
barren	in drill hole B-1	?	quartz, carbonate, epidote, hematite ± bornite, chalcopyrite	–	–	–	–	–

minous sphalerite-galena-chalcopyrite association with rare electrum and acanthite and hematite-quartz association, and finally a sulphosalt-barite stage (5) with barite-quartz and carbonate-sulphosalts associations with a number of various silver minerals. Spatial distribution of the mineralization stages and paragenetic associations on individual veins gave rise to their general mineral and metallic zoning. Koděra (1963, 1969) distinguished in the four vertical zones, with boundaries roughly conform with the surface of the granodiorite subvolcanic intrusion (Fig. 11, Table 3): upper Au-Ag enriched zone, upper Pb-Zn zone, lower Pb-Zn zone and Cu zone. Below the Cu zone the barren zone is present as determined by a deep structural borehole B-1 (Štohl et al., 1990).

Fluids related to the mineralization had variable temperatures, mostly in the range of 200–335 °C, and pressures of 90–20 bars (Kovalenker *et al.*, 1991). Dissolved components were dominated by chlorides (0.3–12 wt% NaCl eq.), but in upper levels sulphate solutions were also present. Precipitation of minerals in veins occurred due to the mixing of magmatic and meteoric waters and frequently also due to the boiling of fluids that has been supported by fluid inclusion and stable isotope studies. Paleodepth calculations based on boiling fluid inclusion assemblages showed that the formation of 2nd stage minerals took place in substantially greater depths (0.75-1.6 km) than that of the 4th stage minerals (0.4–1.1 km), implying a syngenetic uplift of the horst.

Silver-rich Ag-Au ± base metal veins in the surroundings of Hodruša ("Hodruša type") evolved on N–S to NE–SW striking faults in the central, western and northwestern parts of the resurgent horst. The length of individual veins does not exceed 3 km, but many of the veins are much shorter. Veins dipping 30–50° E or SE dominate, the extent of displacement being in the range of 40–200 m. Faults controlling the evolution of veins were lystric, their dip and thickness decrease with increasing depth (Fig. 12). Some of the veins split close to the surface into a number of veinlets and branches, including antithetic ones, creating stockwork-like structures accompanied by extensive alterations. This feature indicates much smaller erosion of veins in comparison with the Štiavnica type veins. The vertical extent of individual veins varies in the range 200-500 m, so their original vertical extent probably did not exceed 800 m. This conclusion along with the fact that the veins evolved in rocks of pre-volcanic basement and in granodiorite suggest a relatively younger evolution following a considerable uplift of the resurgent horst in conditions of a higher thermal gradient. The horizontal displacement component led to the evolution of ore shoots, branching of veins on both ends and to the evolution of quite frequent en-echelon arranged shorter veins with a smaller dip between a pair of master faults. Alteration zones of the veins are more extensive compared to the Štiavnica-type veins, especially in the case of stockwork-like vein structures (Onačila *et al.,* 1993). Metasomatic quartzites and adularia-rich rocks occur along with silicified and argillized rocks. Illite dominates among argillic minerals, passing outward into mixed-layer I/S minerals, smectites and chlorite in the outer zone of propylitic alteration. Carbonates and disseminated pyrite may accompany secondary minerals in all the zones.

Only some of the Hodruša type veins show clearly enough features of a uniform polyascendent mineralization process. Koděra (1965, 1989) has defined 9 mineralization stages. The stages 1, 3, 6 and 8 are pure quartz stages, variably with minor carbonates, base metal sulphides and pyrite. The stages 2, 4, 7 and 9 are dominated by carbonates, variably with minor quartz and sulphides. Onačila *et al.* (1993) claim, that the 2nd stage is enriched in base metal sulphides and minor silver sulphosalts and electrum. Stage 5 is the main ore-bearing one, including pyrite, sphalerite, galena, chalcopyrite, marcasite, enargite, tetrahedrite, wurtzite, silver sulphosalts and electrum. In this stage precious metals may dominate over base metals. The upper parts of the veins are enriched in silver minerals and electrum, while the deeper parts are relatively enriched in base metal sulphides. Typical ores grades were 1–3 g/t Au, 80–200 g/t Ag, 0.02–0.5% Pb, 0.05–1% Zn, 0.01–0.2% Cu (Smolka *et al.,* 1993). Surficial parts of the veins, which were the object of the initial, very successful medieval mining, were considerably enriched by oxidation and cementation processes (up to 60 g/t Au and 3,000 g/t Ag).

Mineralization resulted from fluids of temperatures mostly in the range 210–240 °C and salinities 0–3 wt% NaCl eq. (Koděra *et al.,* 2007), however, veins adjacent to the Štiavnica ore field contain also early mineralization stages produced by signifi-

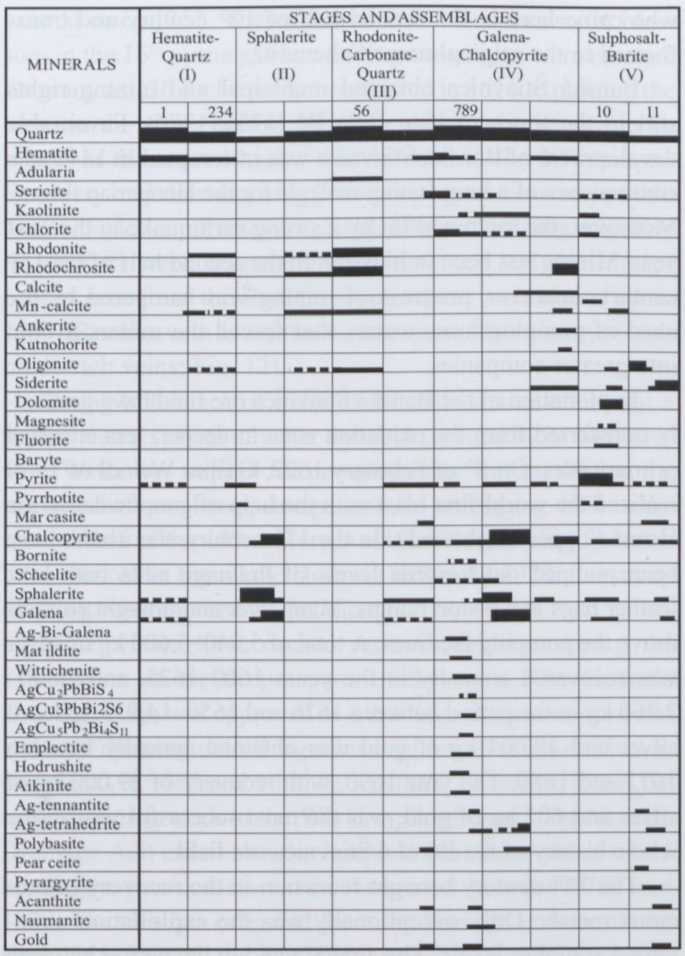

Fig. 10. Paragenetic scheme of the sulphide-rich base metal epithermal veins in the Štiavnica ore field (Kovalenker *et al.*, 1991).

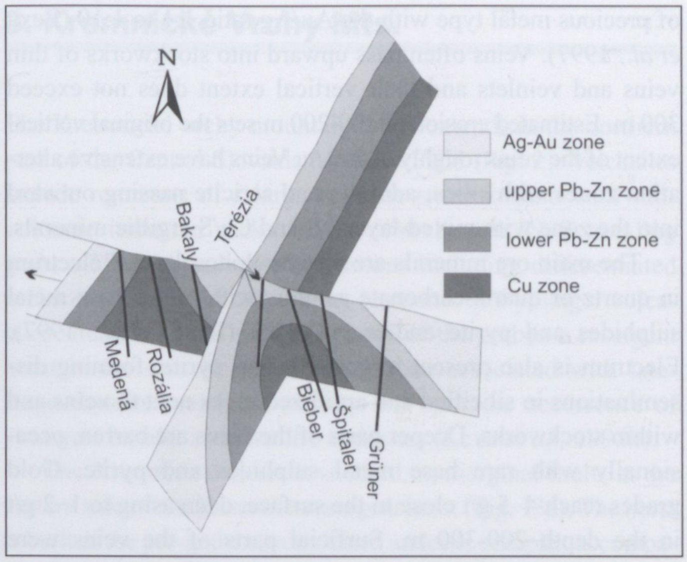

Fig. 11. Vertical zoning of sulphide-rich base metal epithermal veins in the Štiavnica ore field (after Kodĕra, 1963).

cantly higher temperate fluids (260–345 °C) and salinities up to 6 wt% NaCl eq. (Onačila *et al.*, 1993, 1995). These stages also showed significantly greater depths (up to 1.2 km based on boiling fluid inclusions) than later stages (0.5–0.3 km), supporting the idea of syngenetic uplift of the horst and individual evolution of both major ore fields (Štiavnica and Hodruša) in this district. Isotopic composition of fluids indicates mostly meteoric source of fluids (especially the carbonate stages). Compared with the Štiavnica veins, the Hodruša vein system is clearly younger than early mineralization stages of the Štiavnica-type veins, however, their later stages could have been possibly linked with some of the Hodruša mineralization stages.

Au-Ag veins on faults in the marginal parts of the resurgent horst (Banská Belá, Kopanice, Vyhne), sharing features characteristic of the Kremnica low sulfidation epithermal system (therefore labelled as "Kremnica type"). Veins of this type evolved on dominantly N–S striking faults and are probably the youngest in the entire district. Possibly during this stage the uplifted central parts of the resurgent horst were already too elevated for the outflow of hydrothermal fluids. This vein system associates closely in space and time with rhyolite dykes using the same faults or their emplacement (similar to the Kremnica ore field – see below). Mineralization is dominantly

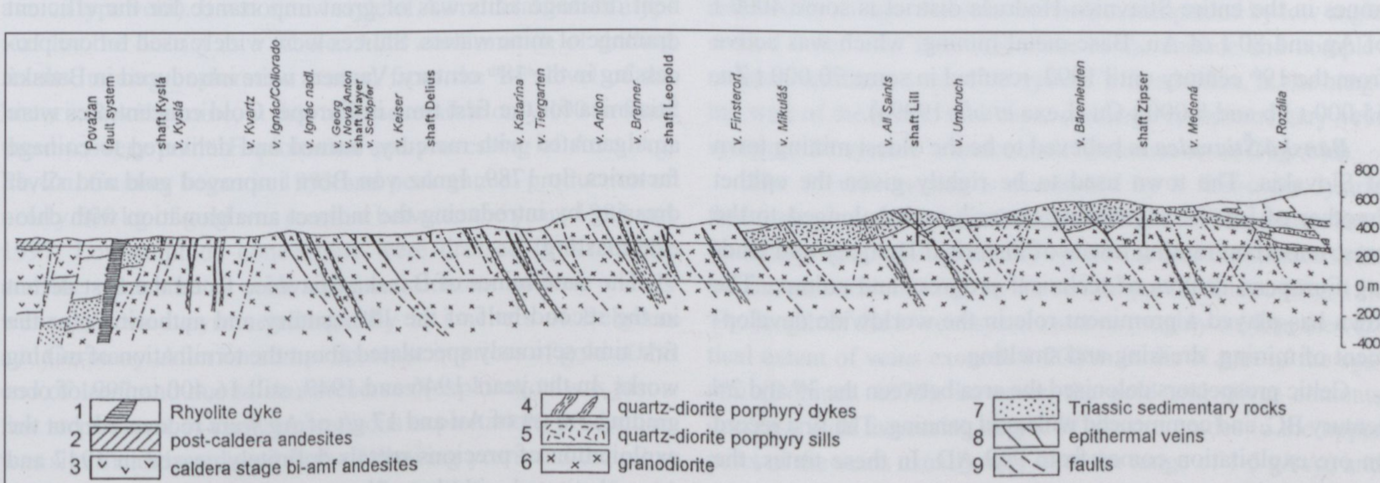

Fig. 12. Transverse sections of the system of silver ± base metal epithermal veins along the Hodruša and Voznica historic adits in the Hodruša ore field (Lexa *et al.*, 1997).

SZTE Klebelsberg Könyvtár SZEGED

of precious metal type with the Au/Ag ratio 1:1 to 1:10 (Lexa *et al.,* 1997). Veins often pass upward into stockworks of thin veins and veinlets and their vertical extent does not exceed 300 m. Estimated erosion of 100-200 m sets the original vertical extent of the veins roughly at 500 m. Veins have extensive alteration zones with silica, adularia and sericite passing outward into the zone with mixed-layer I/S and Ch/S argillic minerals.

The main ore minerals are silver sulphosalts and electrum in quartz or quartz-carbonate gangue, with minor base metal sulphides and pyrite and/or marcasite (Lexa *et al.,* 1997). Electrum is also present in gold-bearing pyrite, forming disseminations in silicified and argillized rocks next to veins and within stockworks. Deeper parts of the veins are barren, occasionally with rare base metal sulphides and pyrite. Gold grades reach 4–5 g/t close to the surface, decreasing to 1–2 g/t in the depth 200-300 m. Surficial parts of the veins were enriched in gold and silver also due to oxidation and cementation processes.

Fluid inclusion and stable isotope data from the westernmost vein Trojkráľová showed origin of the mineralization from boiling of mostly meteoric fluids at 200–230 °C with salinity 0–2 wt% NaCl eq. (Gašparek, 2009). Boiling in shallow depth (~150-250 m) was responsible for gold precipitation and stabilisation of adularia in the upper part of the veins.

2.2 History of mining (after Bakos et al., 2004)

The Hodruša–Štiavnica ore district is one of the largest ore districts in the Carpathian arc, famous for its long-lived silver and gold mining of epithermal veins (post-caldera type) occurring in two major ore fields. Banská Štiavnica ore field is located in the vicinity of the town of Banská Štiavnica and host predominantly the sulphide-rich "Štiavnica type" veins. Hodruša ore field occurs in the vicinity of Hodruša village and hosts predominantly the silver-rich "Hodruša type" veins. Based on archive data, the estimated total historical output of mines in the entire Štiavnica-Hodruša district is some 4000 t of Ag and 80 t of Au. Base-metal mining, which was active from the 19th century until 1992, resulted in some 70,000 t Zn, 55,000 t Pb and 8,000 t Cu (Lexa *et al.,* 1999a).

Banská Štiavnica is believed to be the oldest mining town of Slovakia. The town used to be rightly given the epithet "mother of [medieval] mining towns", as it belonged to the most important mining towns of historical Hungary and leading European centres of technical progress and culture. The town has played a prominent role in the worldwide development of mining, dressing and smelting.

Celtic prospectors colonised the area between the 3rd and 2nd century BC, and commenced with gold panning. The first record on ore exploitation comes from 969 AD. In these times, the Slavic inhabitants have given the most important settlement beneath Paradajz hill the name Štiavnica. The name of the settlement was respected and took over by Saxonian colonists, who came here in the second half of 12th century and transformed to the original name Schemnitz.

Banská Štiavnica obtained municipal and mining rights still in the times of king Bela IV (1235–1270). Favourable development of Banská Štiavnica was interrupted in 1442 as a consequence of a long-lasting struggle for the Hungarian throne. Moreover, the town was hit by a strong earthquake in the next year. Mining has been in blossom in the second half of the 15th century, however, progress of mining was hampered by the need of pumping mine waters that forced the miners to join into greater companies.

Exploitation of the Banská Štiavnica ore field have gradually transferred from the oxidation zone to deeper, less enriched primary ores. On 8th of February 1627, Gaspar Weindl of Tyrol realized the world-first blast with the help of gunpowder in the Horná (Upper) Bieber adit. In the 17th century, the waters have been pumped out towards levels of drainage adits with kits, leather bags and piston pumps. Manpower and draught animals drove the pumping facilities. A total of 5,040–5,600 kg of silver was recovered annually in the years 1600–1625, and 2,800–3,360 kg in the period between 1626 and 1650. 14,933.52 kg of silver and 187.04 kg of gold was obtained annually between 1672 and 1680. The year 1690, with recovery of 29,000 kg of silver and 605 kg of gold, was the most successful year in the whole history of the Banská Štiavnica ore field.

The 18th century brought recession in the recovery of precious metals. Only exceptionally was the exploitation maintained at higher levels. The annual yield in the period between 1740 and 1823 was only 145 kg of gold and 8,900 kg of silver on average. New technological inventions in ore dressing demanded the construction of additional water dams. In the period between 1500 and 1638, only four dams have existed in the surroundings of Banská Štiavnica, but their number increased to 14 in the second half of the 18th century. J. K. Hell's pumping machine based on hydraulic principle and powered by water was a unique device introduced in 1755 in the Amália shaft. The Successive completion of three prominent drainage adits was of great importance for the efficient drainage of mine waters. Sluices were widely used for ore processing in the 18th century. Vanners were introduced in Banská Štiavnica for the first time in Europe. Gold concentrates were amalgamated with mercury, burned and delivered to coinage factories. In 1789, Ignaz von Born improved gold and silver dressing by introducing the indirect amalgamation with chloride roasting.

The state mines of Banská Štiavnica faced the first deficit in the second half of the 18th century and authorities for the first time seriously speculated about the termination of mining works. In the years 1946 and 1947, still 16,400 tonnes of ores grading 3.1 g/t of Au and 17 g/t of Ag were recovered, but the exploitation of precious metals definitely ceased in 1947 and was substituted with that of base metals that lasted until 1992.

The mining of precious metals in the ***Hodruša*** ore field known from the 13th century, but Hodruša settlement were existed since 1352. The exploitation in Hodruša was in blossom in the 16th century, when mining companies were created. As many as 136 such companies existed in 1616 exploiting the veins in the upper part of the town, other veins started to be mined in the second half of the 18th and in the 19th century. Recovery and dressing of gold-silver ores terminated in 1950 due to depletion of reserves. Since 1951, all mining activities in Hodruša were concentrated on recovery and dressing of copper ores from the Rozália mine, where it continued up to 1991 (Rozália vein is on the westernmost Štiavnica-type sulphide-rich veins; Fig. 12).

Owing to the lack of water as the main source of energy, a sophisticated system of water dams, drains and races were created. Water was utilised for pumping mine waters, driving the traction shaft machines, stamps, and for ore jigging. Still in the second half of the 19th century, a total of 25 dressing factories have worked in the whole Hodruša valley. In 1929, the stamp dressing was replaced by flotation.

Mine waters have caused serious problems during the exploitation of the deeper parts of the veins. The Hodruša Drainage Adit, was approved as a drainage adit already in 1494 and was draining out all significant mines in Hodruša. It was completed in 1765 and with the length of 12,149 m, it was the longest mining work in the World in those times. The Voznica Drainage Adit called also the Joseph II Drainage Adit of a 16.5 km lenght was constructed in the period between 1782 and 1878. The adit has extended from the Hron river beneath the Hodruša valley and the Tanád Hill massif to Banská Štiavnica and has drained all significant veins of the entire ore district. In the time of completion, it was again the longest mining work in the World. The New Drainage Adit was driven between 1975 and 1994, with a total length of 13.8 km, with the intention to replace the Voznica Drainage Adit but was never put in action due to termination of mining in Banská Štiavnica.

Caldera-related Au veins in the Rozália mine were unexpectedly discovered in 1988 during a drilling program on the northern continuation of the Bakali vein (sulphide-rich Štiavnica type vein). It was a new style of Au mineralization atypical for the district as a whole. After confirmation of drilling results, mining exploration started from the 14th level of the historic Rozália mine, at that time accessible only 100 m from the discovery point. Exploitation and processing of Au ± Ag, Pb, Zn, Cu ores began in 1993 and peak annual production of nearly 500 kg of gold was reached between the years 1994 and 1997. Low-sulphide concentrate were dressed in Kremnica and the concentrates with increased content of base metals were processed pyrometallurgically in smelters of Belgium and Germany. After on abrupt decrease in prices of gold at the end of 1997 and due to short reserves (exploration was just a few steps ahead of contemporaneous exploitation) production was significantly reduced in the following years and the mine was nearly closed. However, thanks to the recovery of gold prices since 2002 and positive exploration results the exploitation is still in progress.

3. Kremnické Vrchy Mts.

The Kremnické vrchy mountain range extends in the northern part of the Central Slovakia Volcanic Field (Fig. 2). Volcanites include remnants of a large andesite stratovolcano with subvolcanic intrusive rocks in the central zone, N–S trending graben filled by volcanic formations including differentiated rocks in thickness over 1,000 m, remnants of 4 younger volcanoes situated next to marginal faults of the graben a resurgent horst in the central part of the graben associated with late-stage rhyolite magmatic activity and sporadic occurrence of youngest basalts and basaltic andesites (Lexa *et al.,* 1998b).

The Kremnica deposit is situated on marginal faults at the eastern side of the Kremnica resurgent horst (Fig. 13a). The horst is built of the pre-graben propylitised andesite complex accompanied at depth by subvolcanic intrusions of gabbrodiorite, diorite, diorite porphyry and minor quartz-diorite porphyry (16.2–15.0 Ma) (Lexa *et al.,* 1998b). Emplacement of subvolcanic intrusions was accompanied by minor skarn/stockwork base metal mineralization (Böhmer, 1977; Štohl *et al.,* 1994). The horst is surrounded by andesitic rocks of graben fill (15.0–13.5 Ma).

The structure of the horst is dominated by N-S and NE-SW trending normal faults, corresponding to the regional stress field with a strong NW-SE extension during the interval 13.5–9 Ma. Uplift of the horst was contemporaneous with epithermal mineralization (11.1–10.1 Ma; Kraus *et al.,* 1999) and emplacement of rhyolite dykes (12.9–10.7 Ma), with corresponding granite porphyry subvolcanic intrusions at depth. Contemporary rhyolite domes, flows and volcanoclastic rocks occur S of the horst in the northern part of the Žiar tectonic depression.

3.1 Characteristics of epithermal veins of the Kremnické Vrchy Mts.

The system of epithermal veins of low sulphidation type is represented by a major transtension fault accompanied by low angle second order vein structures close to the surface and complementary antithetic veins ("1st system"). In addition, in the hanging wall of the lystric fault there is a large complementary vein system ("2nd system"), underneath Kremnica town (Fig. 13a).

The 1st vein system is dominated by a first-order lystric fault, intruded also by rhyolite dikes (Fig. 14). The mineralised fault dipping 50°-60° gradually opens towards the surface to its maximum width of 80 m in the central part at Šturec (Fig. 15). The length of the 1st vein system attains roughly 6.5 km, the vertical extent of veins exceeds 1 200 m in the N part of the system (Böhmer, 1977), however, the gold and silver contents decrease with increasing depth. While ore grades in the upper parts of the veins usually vary over the range of 1-5 g/t Au and 5-30 g/t Ag (Böhmer, 1966; Veľký, 1992; Bartalský & Finka, 1999), at greater depths they change to 0.5-1 g/t Au, and about 50 g/t Ag, 0.5% Pb, 0.8% Zn, and 0.2% Cu (Knésl *et al.,* 1990).

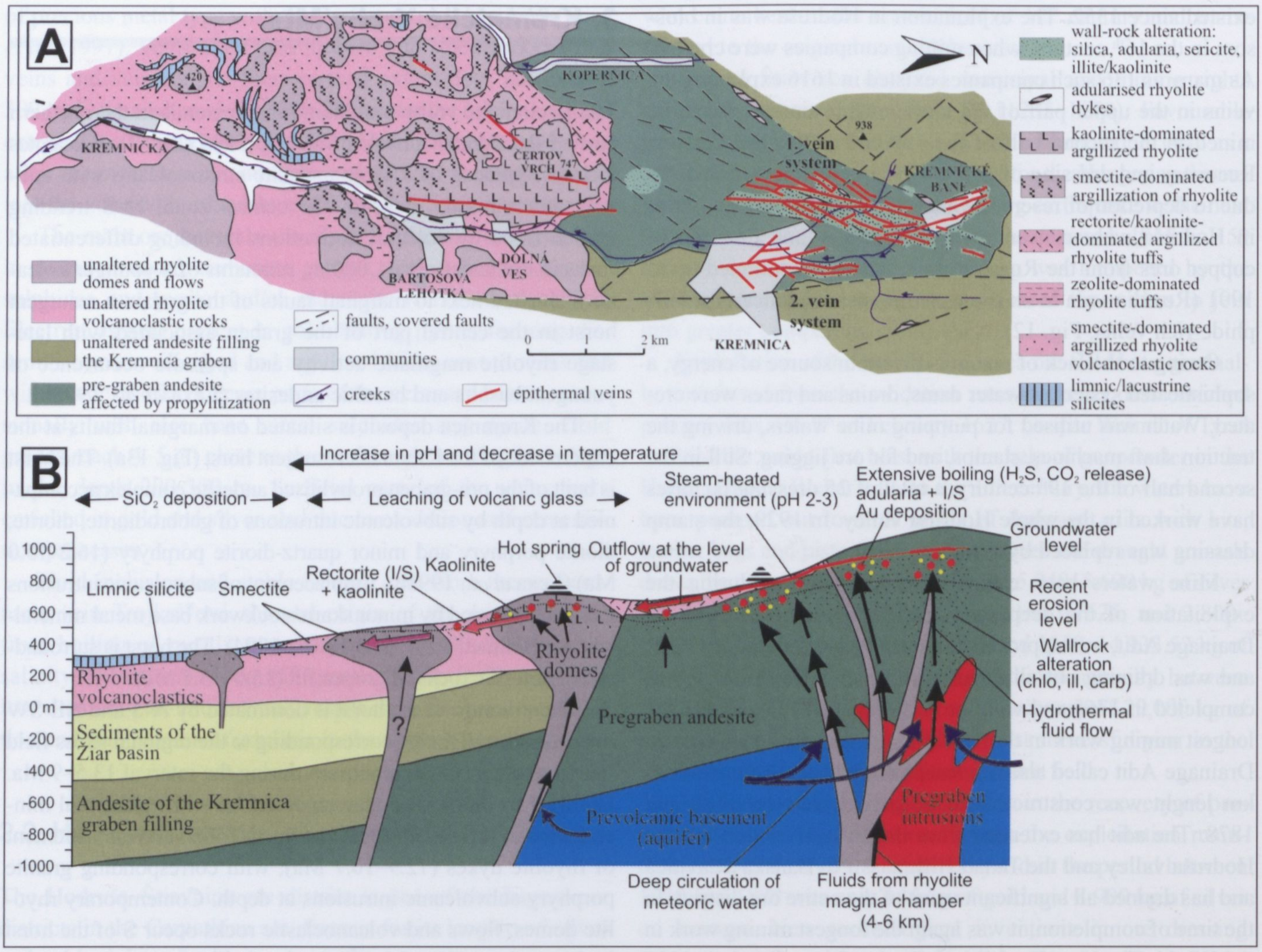

Fig. 13. Geological map (A; after Kraus *et al.,* 1994) and schematic model of the Kremnica hydrothermal system (B).

The main vein structure branches into a funnel-shaped system of veins and veinlets, including complementary antithetic veins (Fig. 14). Low-angle second order vein structures join the 1st order fault on its western side and extend 1-2 km southwestward (sometimes called as 3rd vein system).

Vein filling is represented by banded and cavernous quartz, sometimes with carbonates. Extensive wallrock alteration includes adularia, quartz, I/S, kaolinite, passing outwards into chlorite, smectite, variably with disseminated pyrite and carbonate (Kraus *et al.,* 1994). Mineralization continues with some breaks at least 5 km S from Šturec down to Bartošova Lehôtka village in the form of mineralized quartz/chalcedony veins with up to 1-4 g/t Au (Veľký, 1999). At the Čertov Vrch hill ~3 km S from Šturec hydrothermal breccias cemented by quartz/ chalcedony with cinnabar, minor Au and kaolinite are present, interpreted as a hot spring type mineralization (Fig. 13a). Surrounding rhyolite and rhyolite tuffs contain kaolinite, while south of the hill a deposit of the I/S mineral rectorite occurs (Kraus *et al.,* 1994). Smectite-dominated alterations extend further S, associated with limnic/lacustrine silicites near Stará Kremnička with increased Sb, As, Hg contents.

Mineralogical studies determined two major stages including 6 mineral associations (Böhmer, 1966; Maťo, 1997; Fig. 16). The Au-Ag stage contains an early minor barn carbonate substage (1), two quartz substages (2 and 3) and a pyrite substage (4). Microscopic Au precipitated mostly during the pyrite substage and occurs as electrum or gold in pyrite and quartz in dark quartz-chalcedony bands with fine dispersed pyrite/marcasite. Pyrite and arsenopyrite are the most frequent ore minerals, accompanied by minor galena, sphalerite, chalcopyrite, proustite, pyrargyrite and Ag sulphosalts. In the deeper parts of the veins (250-1000 m in N part of the system) more frequent base metal sulphides are accompanied by rare tellurides (hessite, altaite, stützite, petzite, goldfieldite). Au ± Hg, As stage followed by intensive intermineralization tectonics and fills mainly fissures especially in the hanging wall of the major vein structure. This stage includes a quartz-carbonate substage (5) with predominant dolomite and minor quartz with rare disseminated sulphides, sulphosalts and electrum; and a stibnite substage (6) with common stibnite, pyrite, marcasite in a quartz-chalcedony gangue best developed in the footwall structures (mainly at Šturec).

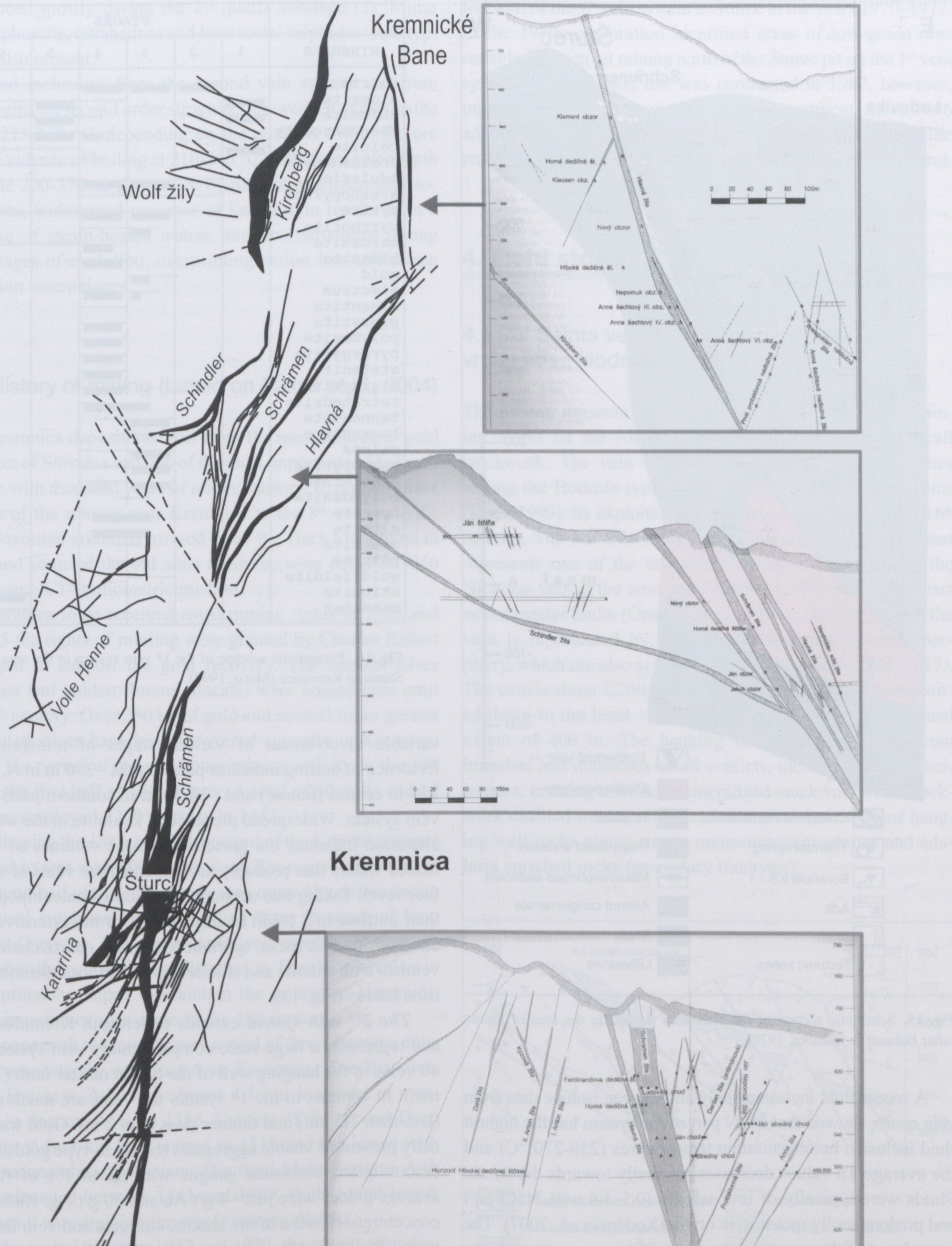

Fig. 14. Schematic map and sections of the 1st vein system at the Kremnica epithermal deposit (based on Veľký *et al.*, 1998 and Kremnica Gold materials)

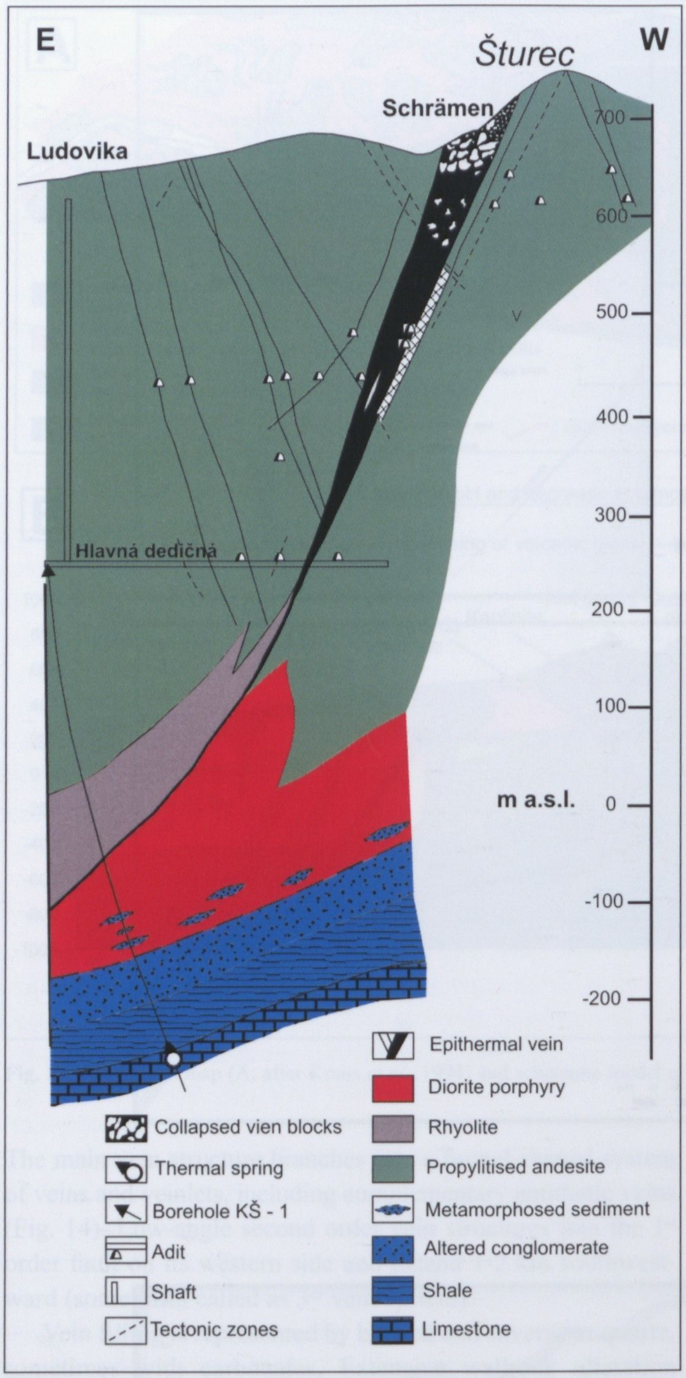

Fig. 15. Schematic section of the Kremnica deposit in the area of Šturec (after Bohmer & Škvarka, 1970).

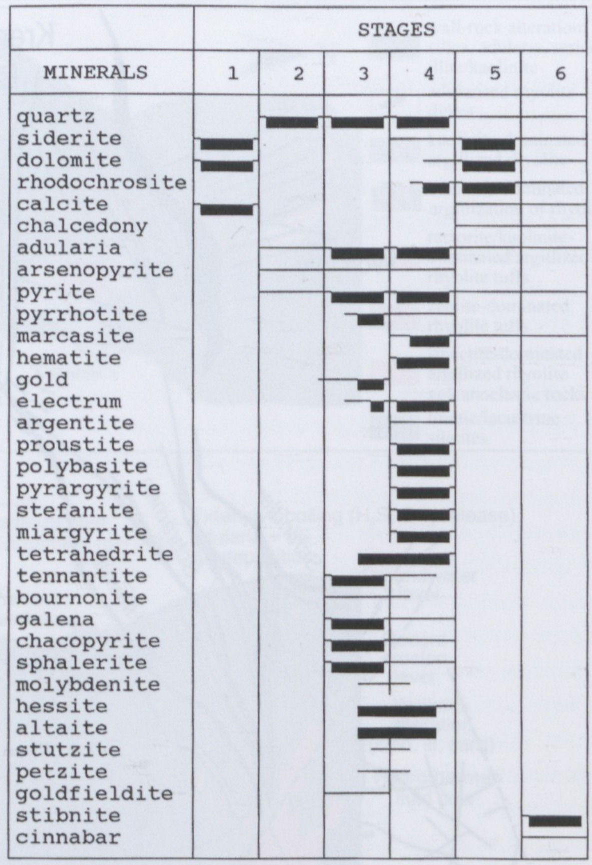

Fig. 16. Paragenetic scheme of the 1st vein system in the area of Šturec in Kremnica (Maťo, 1997).

A recent fluid inclusion study and oxygen isotope data from vein quartz showed that the N part of the system has the highest fluid inclusion homogenisation temperatures (250-270 °C) and the average Th values decreases gradually towards the south. Fluids were typically of low salinity (0.5–1.6 wt% NaCl eq.) and predominantly meteoric in origin (Koděra *et al.*, 2007). The central part of the system in the area of Šturec experienced two episodes of boiling at ~240 °C and ~205 °C, indicative of a long-living hydrothermal system with a syngenetic uplift of the Kremnica horst. Difference in paleotemperatures is related to a progressive increase in the erosion level towards north, with variable involvement of various stages of mineralisation. Evidence of boiling indicates paleodepths ~350 m in N, ~150-350 in central (Šturec) and ~30-50 m in southern parts of the vein system. Widespread presence of kaolinite in the wallrock alteration indicates the presence of large volumes of steam-heated waters that probably accompanied the veins at subsurface level. Taking into account the assumed paleotopography, their outflow to S could be responsible for the extensive alteration of rhyolitic rocks, sporadic low-grade quartz/chalcedony veinlets with stibnite and silicite deposits in local limnic/lacustrine basins (Fig. 13).

The 2nd vein system extends underneath Kremnica town and represents a large scale complementary vein system with 40 veins in the hanging wall of the lystric master fault (1st system). In contrast to the 1st system the veins are much shorter (less than 1.5 km) and thinner (less than 2 m). Gold was typically present as visible aggregates (bonanza-type gold) in cavernous quartz-carbonate gangue with up to 1% of Au, but average grades were just ~4 g/t Au and 30 g/t Ag. Richest Au concentrations were in ore shoots, stringers and vein intersections. Wallrock alteration includes illite, kaolinite, passing outwards into I/S + kaolinite and smectite (Böhmer, 1969).

The evolution of mineral paragenesis was similar to the1st vein system except of the absence of the 1st (carbonate) substage and smaller extent of the 2nd stage of mineralization. Gold was introduced mostly during the 2nd quartz substage (3). Minor Ag-sulphosalts, tetrahedrite and base metal sulphides were typically also present.

Fluid inclusions from the second vein system and from other veins on second order structures showed Th values in the range 215-250 °C, depending on the position within the ore field. Evidence of boiling at 210-240 °C results in a paleodepth estimate 200-370 m. As proven by oxygen and hydrogen isotope data, widespread presence of kaolinite in results from a collapse of steam-heated waters into host structures during later stages of evolution, overprinting earlier low-sulfidation alteration assemblages.

3.2 History of mining (based on Bakos *et al.*, 2004)

The Kremnica deposit has ever been the most important gold producer of Slovakia and one of the most important in Medieval Europe with thousand years of mining history. Historians place outsets of the mining near Kremnica to the 8th century A.D. First Saxonian colonists arrived from the Harz Mountains in 1008 and some of the old adits at Šturec were dated at 1050 years using C14 radiometric method.

Kremnica town received royal mining rights in 1328 and in 1335 the rights of minting were granted by Charles Robert of Anjou to support the gold recovery. The famous silver groschen and golden florens (ducats) were coined here until the 18th century. Over 250 kg of gold and several times greater amount of silver have been recovered annually in Kremnica during the period of the maximum mining activity in the 14th and in the first half of 15th century. A total of 40 mills and 12 smelters employed 1200 workers in 1442.

Following the 15th century the output of the Kremnica mines declined to less than 100 kg per year. Recession of mining in the second half of the 15th century was caused by deteriorating geological conditions and increasing taxes in times of king Mathias Corvinus. The use of explosives, most likely immediately after the world-first application in Banská Stiavnica in 1627, probably helped to maintain the mining at Kremnica, whose importance rose again in the 18th century.

To cope with the mine waters a total of three drainage adits were consecutively constructed in Kremnica. The first one, Upper Drainage Adit was almost 4.5 km long and is mentioned in documents from 1385. Driving of the second Deep Drainage Adit 7 km long started in 1519 and has lasted with intermissions almost 94 years. The third Main Heritage Adit was constructed between 1841 and 1899. With a total length of 15 km it was draining the whole mining district.

In the period between 1947 and 1970, the output of underground mining was only 90-100 kg of Au and 120-130 kg of Ag. Owing to low gold prices in the 1960s underground precious metal mining was stopped in Kremnica. Still approximately 30,000 tonnes of antimony ores were exploited in the footwall of the 1st vein system at Šturec in the years 1970–1972. In the 1970s exploration identified areas of low-grade ores suitable for open pit mining north of the Šturec pit on the 1st vein system. A production test was conducted in 1987, however, mining was to started owing to lack of investment. Since 1996 additional exploration by foreign companies increased the reserves up to 19 Mt of ore with 1.9 g/t Au (www.tournigan.com).

4. Field stops

4.1 All Saints vein and stockwork, Štiavnické vrchy Mts., Hodruša

The mining museum in Hodruša provides access to old mining works on the All Saints vein and related hanging wall stockwork. The vein was one of the most important ones among the Hodruša type silver ± base metal epithermal veins (Lexa, 1999). Its exploitation took place mostly during the 16th century. The NE-SW striking vein dipping 25-35° southeast represents one of the en-echelon arranged veins among the Nicholas vein at the west and Rummel-Hoffer vein at the east as the master faults (Onačila *et al.*, 1993). The footwall of the vein is represented by granodiorite and quartz-diorite porphyry, which are also at the hanging wall of the vein (Fig. 17). The vein is about 1,200 m long and 2-3 m thick. It was exploited down to the level +224 m, making accessible the vertical extent of 400 m. The hanging wall includes several vein branches and numerous small veinlets, including the antithetic ones, creating a weakly mineralized stockwork. The stockwork enabled intense silicification and adularization of hanging wall rocks giving rise to metasomatic quartzites and adularia enriched rocks (secondary trachytes).

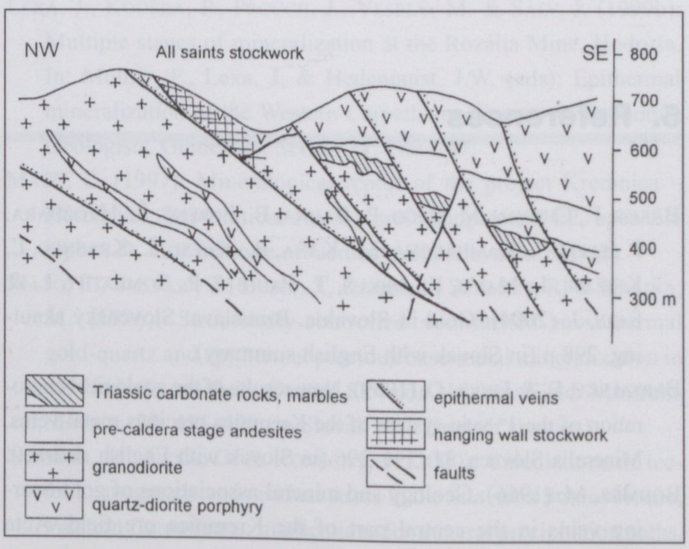

Fig. 17. Section along the All Saints vein and stockwork in Hodruša (Onačila *et al.*, 1993).

The vein is formed by quartz or quartz-carbonate gangue with sulphides and silver sulphosalts, which are concentrated in the lower and upper parts of the vein around the central mass of quartz (Onačila *et al.*, 1993). Mineable ore continued sometimes also into the hanging wall branches and stockwork. Mineralization is represented by a complete set of stages with minerals described above. Electrum of the fineness 470–600 is present in the form of minute grains (5–200 micrometers) in base metal sulphides, along their boundaries and along boundaries of quartz and carbonate grains. Electrum as well as younger silver sulphosalts also replace the older base metal sulphides. Grade of the ore at the lowermost horizon was 0.62% Pb, 1.21% Zn, 0.26% Cu, 0.52 g/t Au and 36.1 g/t Ag (Smolka *et al.*, 1993).

4.2 Špitaler vein, Štiavnické vrchy Mts., Banská Štiavnica – Glanzenberg

The locality represents surficial outcrops of the Špitaler vein, affected by medieval excavations (Fig. 10). The vein is the longest and the most complex one among the Štiavnica type base metal epithermal veins, exposed here in the upper lead-zinc zone (Lexa, 1999). It is striking NNE-SSW, dipping 60-75° eastward. The vein has numerous hanging wall and footwall branches, forming the vein system up to 50 m wide. Its thickness at the locality is up to 5 m, however, it is split into several closely spaced parallel branches. Thin veinlets follow eventually also the set of antithetic complementary fractures.

Surrounding rocks are propylitized pyroxene andesites of the pre-caldera stage. Close to the vein they are affected by sericitization, adularization and silicification. Zones enriched in pyrite are conspicuous due to hyperfine argillization and bleaching.

Remnants of the quartz-carbonate-sulfide vein filling show variably banded, drusy, cocard or breccia textures. Intermineralization faulting is indicated by crosscutting features and tectonic brecciation. Mineral paragenesis is dominated by base metal sulphides of the 2nd mineralization stage, quartz and carbonates of the 4th mineralization stage and minor silver sulphosalts and electrum of the 5th mineralization stage (Lexa *et al.*, 1997).

4.3 Schrämen vein, Kremnické vrchy Mts., Kremnica – Šturec

At Kremnica–Šturec the thickest segment of the main vein of the 1st vein system is exposed, reaching a thickness of 80 m (Fig. 13). The large pit over this segment of the vein is not a result of surficial excavations, but rather it originated by the collapse of extensive underground mining workings from Medieval times during an earthquake (Lexa & Bartalský, 1999). As much as 1 million ounces of gold were mined here without the use of explosives. Medieval chisel- and hammer-made adits are still visible in the western wall of the pit. At the base of the wall there are also entrances to adits, which were used in the 1960s to explore and exploit footwall stibnite-bearing veins. Recently, a mining museum was opened underground of Šturec by restoring the former exploration adit Andrej.

The recent excavations in the southern wall of the pit show the complete thickness of the main vein. Argillized andesites of the hanging wall are exposed at the cuts of the access road, while altered rocks of the footwall are exposed in the western wall of the pit. Figure 5 shows a section of the vein here. It is important to note that in this segment of the vein a considerable portion of the reserves is represented by the broken zone of collapsed mine workings. The gold content of the gangue varies from less than 1 g/t in the plain white quartz to over 5 g/t in grey quartz and hydrothermal-explosion breccias.

At the northern entrance to the pit one of the rhyolite dikes affected strongly by adularization is exposed. An assay shows the gold content to be 2 g/t. A small pit further northward marks the site of the former shaft.

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Appendix – Itinerary for IMA2010 SK3 Field trip

Saturday, August 28, 2010 (Day 1)

08.00–11.30	Travel to Slovakia (via Šahy)
11.30–13.00	Arrival to Banská Štiavnica, lunch, explanation of geology and metallogeny of the Štiavnica stratovolcano
13.00–13.30	Travel to Hodruša
13.30–16.00	Field stop 1: Underground visit to medieval works on the All Saints epithermal Ag-Au vein
16.00–18.00	Field stop 2: Open pit (medieval excavations) on the Špitaler base- and precious metal epithermal vein
18.00–19.30	Accommodation and dinner in Banská Štiavnica

Sunday, August 29, 2010 (Day 2)

08.00–09.30	Mineralogical museum in Banská Štiavnica
09.30–10.30	Travel to Kremnica
10.30–12.30	Field stop 3: Kremnica-Šturec open pit epithermal gold vein mineralization
12.30–13.30	Lunch in Kremnica
13.30–16.00	Visit of historical town, mint museum and castle; alternatively underground visit to mining museum at Šturec (Andrej adit)
16.00–20.00	Travel to Budapest (via Šahy)

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ACTA MINERALOGICA-PETROGRAPHICA FIELD GUIDE SERIES

VOLUME 29 2010

HU ISSN 0324-6523
HU ISSN 2061-9766

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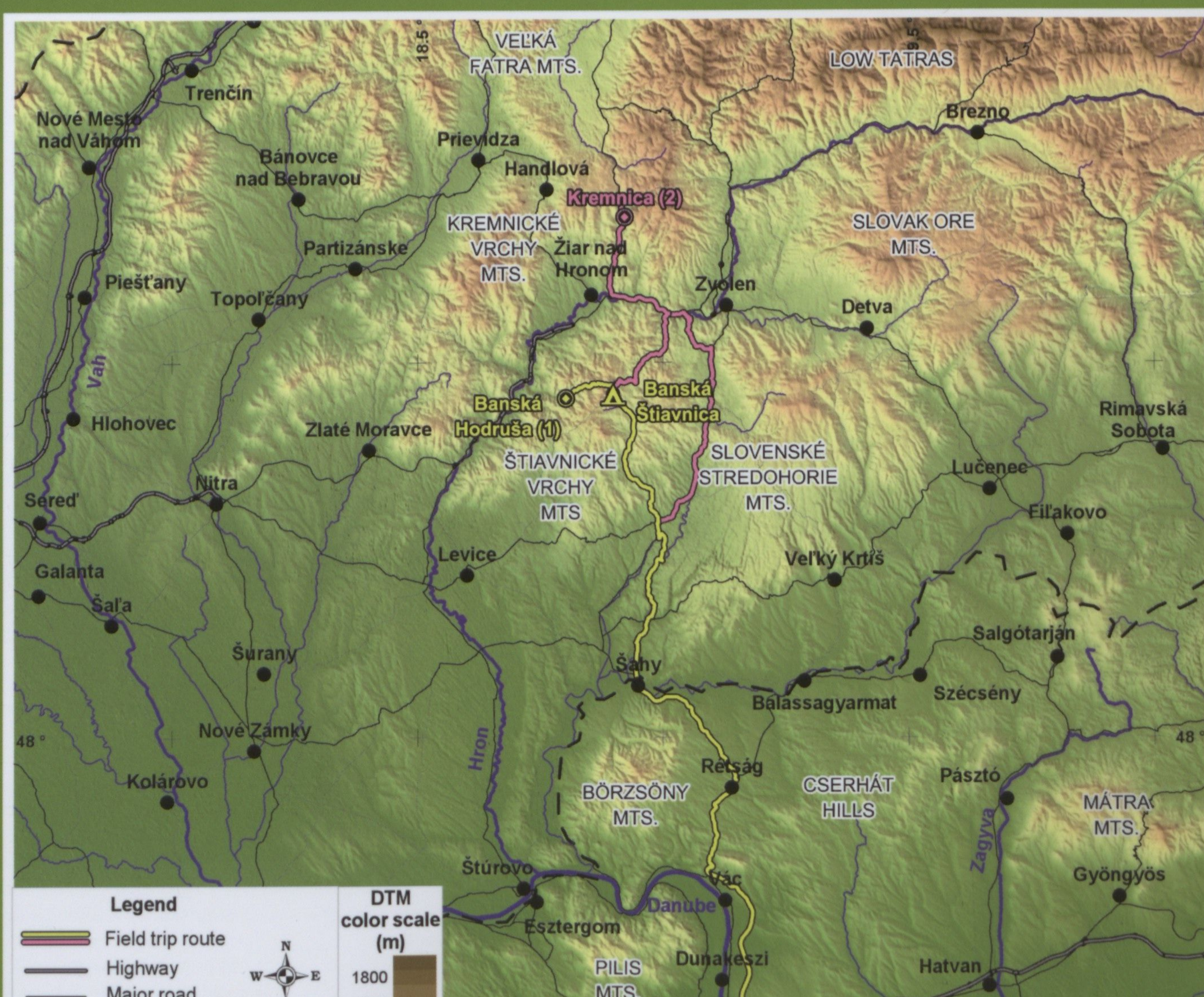

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